System size, energy and centrality dependence of strange hadron elliptic flow at STAR

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Abstract. The elliptic flow (v_2) pattern in terms of hadron mass and transverse momentum p_{T} is qualitatively described for $p_{\mathrm{T}} < 2$ GeV/c by ideal hydrodynamics in Au + Au collisions at RHIC. In addition, for $p_{\mathrm{T}} = 2 - 6$ GeV/c the measured v_2 follow a universal scaling by the number of quarks explained by quark coalescence/recombination models. These observations suggest that a partonic collectivity develops in the matter in early stage of heavy ion collisions. Centrality as well as system size and energy dependence of the v_2 is important to shed light on the underlying collision dynamics in heavy ion collisions. We present the measurements of centrality dependence of v_2 at $\sqrt{s_{NN}} = 200$ and 62.4 GeV in Au + Au and Cu + Cu collisions for K_S^0, ϕ, Λ, Ξ and Ω at STAR experiment. We focus on the recent Cu + Cu results and discuss the centrality dependence of v_2 as well as the number of quark scaling as a function of transverse kinetic energy at different system size and energies. We also discuss the eccentricity scaled v_2 for identified hadrons and implications that ideal hydrodynamical limit has not been reached at RHIC.

1. Introduction

Elliptic flow is expected to be one of the most sensitive observable to study early stage of heavy ion collisions at Relativistic Heavy Ion Collider (RHIC), see recent review in [1]. The elliptic flow is defined by the second harmonic Fourier coefficient of azimuthal distribution of produced particles with respect to the reaction plane

$$v_2 = \langle \cos(2\phi - 2\Psi_{\mathrm{RP}}) \rangle \,, \tag{1}$$

where ϕ is the azimuth of particles in the laboratory frame, Ψ_{RP} is the azimuthal angle of reaction plane which is determined by the direction of impact parameter and beam axis [2]. Brackets denote the average over all particles and events. In Au + Au collisions at RHIC, it has been found that heavier hadrons has smaller v_2 than lighter hadrons for transverse momentum $p_{\mathrm{T}} < 2$ GeV/c, which is qualitatively explained by hydrodynamical models [3]. Above $p_{\mathrm{T}} = 2$ GeV/c, the v_2 had a reversed trend where protons and Λ's have larger v_2 than the charged mesons [4, 5]. The reversed trend can be well described by quark recombination/coalescence models [6, 7, 8] that indicate the v_2 has already developed during the early partonic stage prior to the hadronization. It is important to study the systematics of v_2, such as system size, beam energy as well as centrality dependence, in order to understand the underlying collision dynamics in heavy ion collisions.

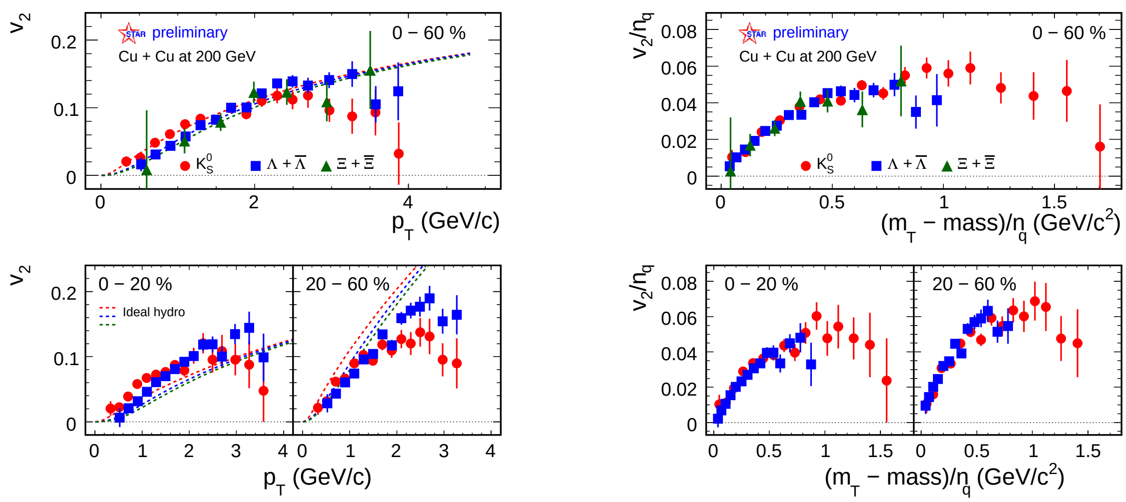
2. Data Analysis

In this analysis, we used minimum bias 24 M events in Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV taken at STAR experiment. The event centrality was determined by the uncorrected charged particle multiplicity measured by the main TPC within pseudorapidity $|\eta| < 0.5$. Particle identifications were performed by the energy loss in the main TPC that enable us to separate K_S^0, Λ and Ξ in $0.2 < p_{\mathrm{T}} < 4$ GeV/c. Event plane method [2] was used to measure v_2 at midrapidity. The v_2 can be expressed as

$$v_2 = \frac{\left\langle \cos(2\phi - 2\Psi_2^{\mathrm{EP}}) \right\rangle}{\langle \cos(2\Psi_2^{\mathrm{EP}} - \Psi_{\mathrm{RP}}) \rangle}, \tag{2}$$

where Ψ_2^{EP} denote the second harmonic event plane determined from elliptic flow, and brackets represent the average over detected particles and events. Event plane was determined by using the forward time projection chamber (FTPC) covered at $2.5 < |\eta| < 4$. Since the FTPC has a rapidity gap from the main TPC region, it can reduce the non-flow contributions that are not correlated with the reaction plane, such as di-jets and resonance decays etc. The denominator in (2) is defined as an event plane resolution that is about 0.18 in midcentral Cu + Cu collisions. We also analyzed the data in Cu + Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV, which has 12.5 M minimum bias events. The event plane resolution was by a factor of 2 smaller than that at 200 GeV due to lower multiplicity.

3. Results



(a) v_2 vs p_{T} (b) v_2/n_{q} vs $(m_{\mathrm{T}} - mass)/n_{\mathrm{q}}$

Figure 1. (a) The v_2 as a function of p_{T} for K_S^0, $\Lambda+\bar{\Lambda}$, $\Xi+\bar{\Xi}$ in 0 - 60 % (top), 0 - 20 % and 20 - 60 % centralities (bottom). Dashed lines represent ideal hydrodynamical calculation [9]. Only statistical errors are shown. (b) Number of quark scaling of v_2 as a function of $m_{\mathrm{T}} - mass$ in 0 - 60 % (top), 0 - 20 % and 20 - 60 % (bottom). Data symbols are the same as those in (a).

Figure 1 (a) shows the v_2 for K_S^0, $\Lambda+\bar{\Lambda}$ and $\Xi+\bar{\Xi}$ as a function of p_{T} in different centrality selections. We have observed that Λ has smaller v_2 than K_S^0 below $p_{\mathrm{T}} = 2$ GeV/c in Cu + Cu collisions. For $p_{\mathrm{T}} > 2$ GeV/c, however, Λ v_2 become larger than that of K_S^0. We have also found Ξ has sizable v_2 in minimum bias 0 - 60 % centrality. Results were compared to an ideal hydrodynamical calculation with the first order phase transition from the QGP to the hadron phase. The ideal hydrodynamical model does not describe the centrality dependence of our data. For 0 - 20 %, the model under-predicts our data and for 20 - 60 %, it over-predicts the v_2. Effects not included in the model which may be relevant are geometric fluctuations in the initial conditions (particularly important in central collisions) and finite viscosity effects. It remains to be seen if these effects can account for the difference between the models and data. Figure 1 (b) shows the number of quark (NQ) scaling of v_2 as a function of transverse mass minus particle mass $m_{\mathrm{T}} - mass$, namely both vertical and horizontal axes are divided by the number of valence quarks for each hadron. One can see that all measured hadrons lie on the universal curve up to $p_{\mathrm{T}} = 4$ GeV/c in all centrality bins. This results indicate that the v_2 has already established in the partonic stage in Cu + Cu collisions.

Figure 2 show the comparison of v_2 for K_S^0 and $\Lambda+\bar{\Lambda}$ at $\sqrt{s_{NN}} = 200$ and 62.4 GeV in Cu + Cu collisions (left panel). For comparison, results in Au + Au collisions are presented in right panel [10, 11]. We found that the measured v_2 at $\sqrt{s_{NN}} = 200$ GeV are consistent with those at $\sqrt{s_{NN}} = 62.4$ GeV in both Cu + Cu and Au + Au

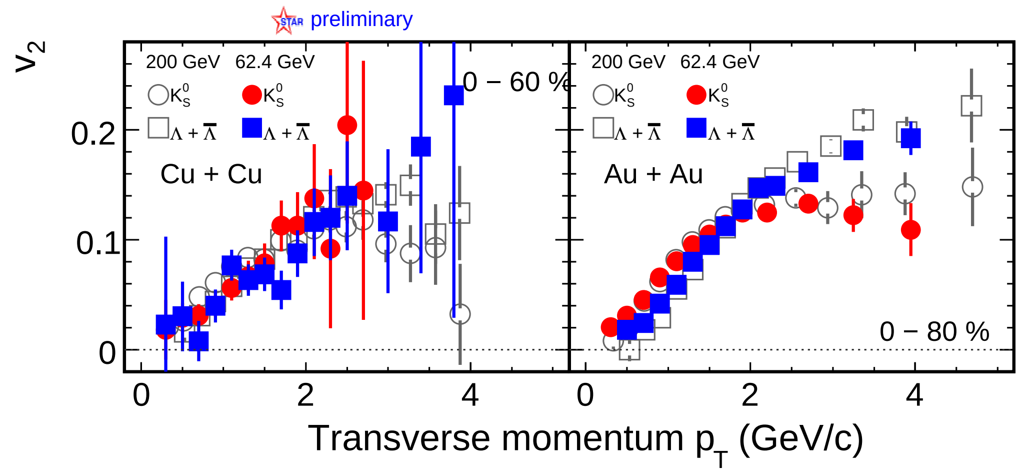


Figure 2. Comparison of $v_2(p_T)$ for K_S^0 and $\Lambda+\bar{\Lambda}$ in 0 - 60 % centrality at $\sqrt{s_{NN}}$ = 200 GeV with those at 62.4 GeV in Cu + Cu (left) and Au + Au collisions (right). The v_2 in Au + Au collisions are taken from [10, 11]. Only statistical errors are shown.

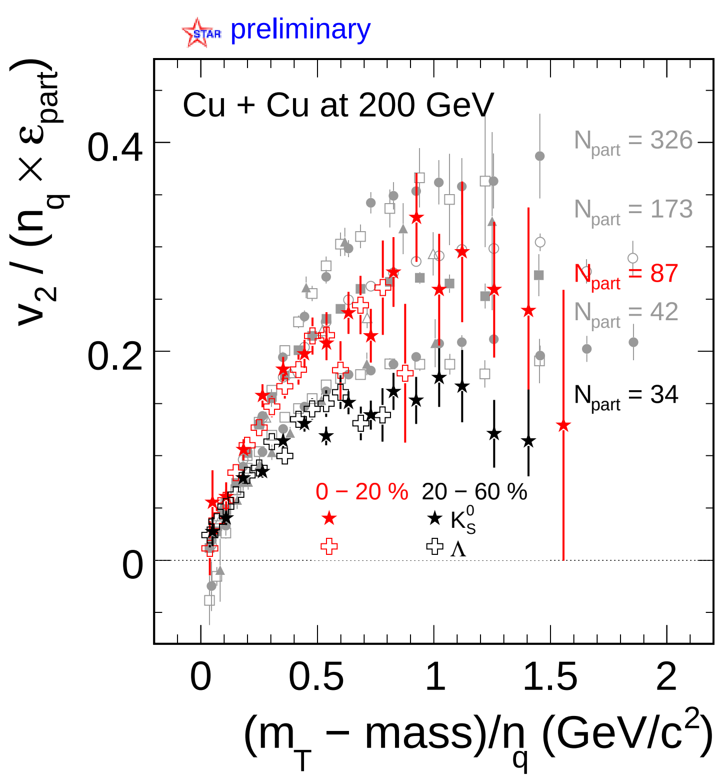


Figure 3. Number of quark scaling of v_2 divided by participant eccentricity ε_{part} for K_S^0 and $\Lambda+\bar{\Lambda}$ as a function of $m_T - mass$ in Cu + Cu collisions. For comparison, results in Au + Au collisions are also plotted.

collisions.

Figure 3 shows the eccentricity scaled v_2 for K_S^0 and $\Lambda + \bar{\Lambda}$ as a function of $m_{\mathrm{T}} - mass$. In order to compare different particle species, NQ scaling was also applied. Since the event plane at the FTPC was determined by particles from participant nucleons, appropriate initial geometrical anisotropy should be participant eccentricity ε_{part} that include event-by-event position fluctuation of participants [12]. The scaled v_2 in 0 - 20 % appeared to be larger than those in 20 - 60 %, which indicate that stronger collective flow has developed in more central collisions. In addition, scaled v_2 in Cu + Cu collisions are consistent with that in Au + Au collisions with similar number of participant N_{part}. This result suggest the observed v_2 is determined not only by initial geometry, but also by the N_{part}. Therefore, it is important to understand whether the v_2 in most central Au + Au collisions reach ideal hydrodynamical limit or not. Because ideal hydrodynamical models predict v_2 is only determined by the initial spatial anisotropy.

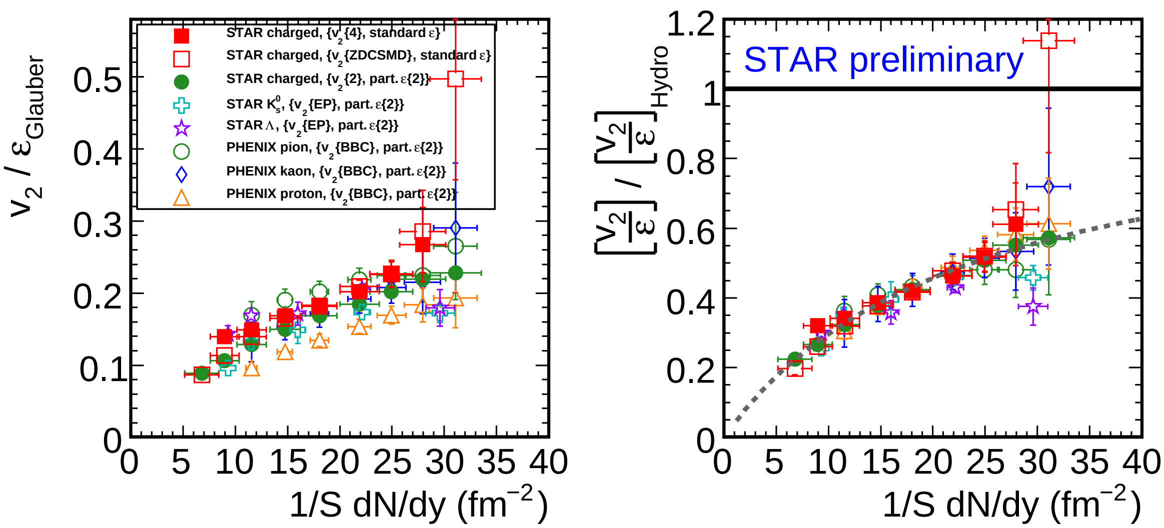


Figure 4. (Left) v_2/ε as a function of transverse number density $(1/S)dN/dy$ for different particle species from STAR and PHENIX. STAR results include preliminary $v_2\{4\}$, $v_2\{\mathrm{ZDCSMD}\}$ in Au + Au collisions as well as v_2 for K_S^0 and Λ in Cu + Cu collisions, and published $v_2\{2\}$ [13], v_2 for K_S^0 and Λ [4]. PHENIX results were taken from [14]. Error bars denote quadratic sum of statistical and systematic uncertainties. (Right) v_2/ε divided by extracted hydrodynamical limit from the fit as a function of transverse number density $(1/S)dN/dy$. Dashed line represent the simultaneous fit for all measured v_2 by (3).

Figure 4 show the comparison of v_2/ε as a function of transverse number density $(1/S)dN/dy$ for different particle species in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX and STAR experiments. Published STAR and PHENIX results were taken from [4, 13, 14]. In order to extract the ideal hydrodynamical limit, we have used

the formula based on a transport model with a finite Knudsen number [15]

$$\frac{v_2}{\varepsilon} = \left(\frac{v_2}{\varepsilon}\right)_{\text{Hydro}} \left(\frac{1}{1 + K/K_0}\right), \quad \frac{1}{K} = \frac{\sigma c_s}{S}\frac{dN}{dy}, \tag{3}$$

where $(v_2/\varepsilon)_{\text{Hydro}}$ is the ideal hydrodynamical limit of v_2, K is the Knudsen number, c_s is the speed of sound, σ is the partonic cross section, S is the transverse area of collision zone and dN/dy is the total hadron multiplicity. We adopted $K_0 = 0.7$ and $c_s = 1/\sqrt{3}$ in order to reproduce the transport model calculation [16]. Hydrodynamical limits were extracted for different hadrons by fitting the available v_2 simultaneously, where we assumed σ is the same for all hadrons. Right panel in Figure 4 shows the ratio of v_2 to the resulting hydrodynamical limit from the fit as a function of $(1/S)dN/dy$. The ratio should be 1 when v_2 reach hydrodynamical limit. We found that the ratio converge into a universal curve and ideal hydrodynamical limit has not been reached even at the most central collisions at RHIC.

4. Conclusions

In summary, we have measured v_2 for K_S^0, $\Lambda + \bar{\Lambda}$ and $\Xi + \bar{\Xi}$ at $\sqrt{s_{NN}} = 200$ GeV in Cu + Cu collisions. We found that Λ has smaller v_2 than K_S^0 below $p_{\text{T}} = 2$ GeV/c, whereas the trend was reversed above $p_{\text{T}} = 2$ GeV/c. The measured hadrons follow the number of quark scaling as a function of $m_{\text{T}} - mass$ in Cu + Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. This result is consistent with the idea that collective flow has been established in the partonic stage before the hadronization takes place. The v_2 at $\sqrt{s_{NN}} = 62.4$ GeV were consistent with those in $\sqrt{s_{NN}} = 200$ GeV in Cu + Cu collisions. We observed that eccentricity scaled v_2 was larger in more central events in Cu + Cu collisions, which indicate that stronger collective flow was developed in more central collisions. Finally, from the comparison of the data with a transport model approach, we found that ideal hydrodynamical limit has not been reached even at the most central collisions at RHIC.

[1] S.A. Voloshin, A.M. Poskanzer and R. Snellings, (2008), arXiv:nucl-ex/0809.2949.
[2] A.M. Poskanzer and S.A. Voloshin, Phys. Rev. C58 (1998) 1671.
[3] P. Huovinen et al., Phys. Lett. B503 (2001) 58.
[4] STAR Collaboration, J. Adams et al., Phys. Rev. Lett. 92 (2004) 052302.
[5] PHENIX Collaboration, S.S. Adler et al., Phys. Rev. Lett. 91 (2003) 182301.
[6] D. Molnar and S.A. Voloshin, Phys. Rev. Lett. 91 (2003) 092301.
[7] R.C. Hwa and C.B. Yang, Phys. Rev. C67 (2003) 064902.
[8] R.J. Fries et al., Phys. Rev. Lett. 90 (2003) 202303.
[9] P. Huovinen, Private communication , $T_c = 170$ MeV, $T_f = 125$ MeV, first order phase transition, EOS Q.
[10] STAR Collaboration, B.I. Abelev et al., Phys. Rev. C77 (2008) 054901.
[11] STAR Collaboration, B.I. Abelev et al., Phys. Rev. C75 (2007) 054906.
[12] PHOBOS Collaboration, S. Manly et al., Nucl. Phys. A774 (2006) 523.
[13] STAR Collaboration, J. Adams et al., Phys. Rev. C72 (2005) 014904.
[14] PHENIX Collaboration, M. Issah and A. Taranenko, (2006), nucl-ex/0604011.
[15] R.S. Bhalerao et al., Phys. Lett. B627 (2005) 49.
[16] C. Gombeaud and J.Y. Ollitrault, Phys. Rev. C77 (2008) 054904.